Modelling of residual deformations, failure and delaminations in SPS ZrB_2/SiC UHTCMC in complex stress states

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Abstract

Ultra-High Temperature Ceramic Matrix Composites (UHTCMC) are lightweight materials with superior temperature, oxidation, and thermal shock resistance, together with a noticeable damage tolerance. For these qualities of theirs, UHTCMC are suited for hot structures applications, such as nozzles of rocket engines, turbine blades of jet engines, nose and leading edges of supersonic vehicles, and for all those components that have a structural role in severe environmental conditions. Nonlinearities and permanent deformations were already observed in UHTCMC and they were related to the presence of severe Residual Thermal Stresses (RTS), which arose during the manufacturing process. In this work, the nonlinear behavior of $C_f - ZrB_2/SiC$ sintered by Spark Plasma Sintering (SPS) was investigated by means of tensile tests and bending tests on specimens with different stacking sequences. Loading/unloading cycles were performed to investigate the presence of residual deformations. Then, ring-on-ring tests were performed on cross-ply disk specimens to evaluate the material behavior under a stress state with a strong biaxial component. A Finite Element (FE) model was set up to analyze the experimental results. An elastoplastic constitutive law was developed based on a modified pressure-dependent Hill yielding criterion, which considers the orthotropic nature of the material, while a Cohesive Zone Model (CZM) was used to simulate the development of delaminations between the plies. The results of tensile and bending tests evidenced three different regimes in the mechanical response of the materials: a first elastic region, followed by a plateau with severe reduction of the tangent modulus and development of residual deformations, and, at the end, a recovery of stiffness until the final failure. The slope of the loading/unloading cycles, performed in the plateau region, showed the same slope of the elastic regime, without reduction of the secant modulus. The disk specimens, tested in ring-on-ring mode, showed extended delaminations, simultaneously developed in different layers due to the transverse shear, relevant permanent deformations, and a significative reduction of the flexural strength. In the FE models, the elastoplastic law was tuned by using the results of the tensile and bending tests, and it was used to model all the specimens. Both the reduction of strength due to biaxiality and the cohesive strength of the interlamina have an influence on the failure of the disks and the model was used to delve into their relationship. As a result, a univocal combination of flexural strength reduction and CZM parameters was found, capable of reproducing the failure of the disks and their post-failure behavior. The experimental/numerical correlation, the morphology of the simulated failure and the damage of the cohesive layers are shown in Figure 1.

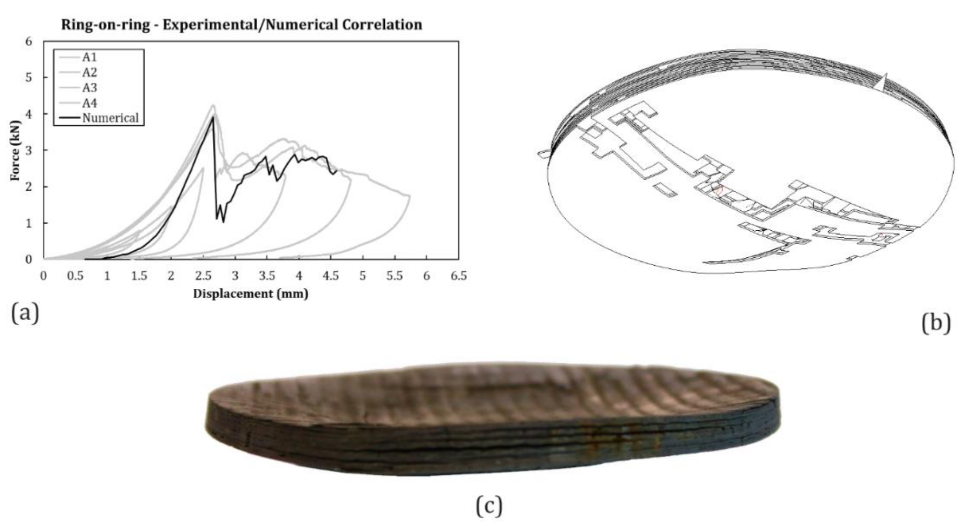

Figure 1. (a) Correlation between experimental and numerical results of ring-on-ring tests. (b) Simulated fracture in the lower layers subjected to tensile load. (c) Multiple delamination in a disk specimen after the ring-on-ring test.